Climate Impact of Black Carbon emitted from Energy Consumption in the World's Regions

M. Shekar Reddy[1,2] and Olivier Boucher[1,3]

[1]Laboratoire d'Optique Atmosphérique, CNRS, USTL, Villeneuve d'Ascq, France.
[2]Now at NOAA-Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA.
[3]Now at Hadley Centre, Met Office, Exeter, United Kingdom.

Abstract. We have used the Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) to estimate the contribution of different regions to global black carbon (BC) atmospheric burden and direct radiative forcing (DRF). On the global scale, fossil fuels and biofuels account for 66% and 34% of energy-related BC atmospheric burdens, respectively. Following the emissions, East and South Asia together contribute more than 50% of global atmospheric absorption by BC (+0.5 Wm^{-2}). Europe is the largest contributor (63%) to the BC deposition over the high latitudinal regions. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation.

1. Introduction

The importance of atmospheric aerosols in the global climate change is now well recognized [*Ramaswamy et al.*, 2001]. Black carbon (BC) exerts a positive forcing at the top of the atmosphere (TOA) as opposed to sulfate which exerts a negative forcing. In the recent years there has been increased attention in the aerosol research community about the potential of BC for global warming through direct effects and change in the albedo of ice and snow [*Jacobson*, 2004; *Hansen and Nazarenko*, 2004]. Black carbon is only emitted from combustion sources in contrast to sulfate and organic carbon (OC) which are also emitted from natural sources. The major sources of BC are from fossil fuels and biomass burning for domestic energy (biofuels) [*Bond et al.*, 2004]. Emissions from open biomass burning are not considered in this study.

The fossil fuel sources are primarily concentrated over the developed countries, India, and China, while biofuels sources dominate over the developing countries including India and China. The atmospheric fate and climate impacts of BC from different regions could differ considerably. Understanding the radiative and climate impacts of BC from different geographical regions is a prerequisite for mitigation options. It is also of interest to understand the intercontinental transport of pollutants and influence on air pollution and regional climate effects under the Convention on Long-range Transboundary Air Pollution (CLRTAP) and Hemispheric Transport of Air Pollution (HTAP) [*United Nations*, 2004].

We have recently presented a study of global carbonaceous aerosol cycle and direct aerosol radiative forcing in the Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) [*Reddy and Boucher*, 2004; *Reddy et al.*, 2005a, 2005b]. Here we extend this work to estimate the radiative impacts of BC from energy sources (fossil fuels and biofuels) emitted from different regions of the world.

2. Method

We use the LMD GCM for simulating the BC transport and radiative effects of BC. The LMD GCM is a grid-point model with a resolution of 3.75° in longitude and 2.5° in latitude with 19 vertical layers. The carbonaceous aerosols transport in this model has been thoroughly described and evaluated in *Reddy and Boucher* [2004]. Here we use BC emissions from recent estimates of *Bond et al.* [2004] allowing to separate the fossil fuel and biofuel sources. The BC emissions from fossil fuels and biofuels are regionally tagged: South America (SAM), North America (NAM), Africa (AFR), Europe (EUR), West and Central, Asia (WCA), South Asia (SAS), East Asia (EAS), Australia and Pacific Islands (AUP), and Oceanic Regions (OCE). Note that over the oceans BC is emitted only from shipping activities. Similar to our previous studies simulations are carried out by nudging the horizontal model winds to 6 hourly winds from ECMWF analyzes with a relaxation time of 0.1 days [*Hauglustaine et al.*, 2004]. Simulations are done for the year 2000 after allowing two months of spin up. The model setup is same as described in *Reddy et al.* [2004] and *Reddy et al.* [2005a, 2005b] but with BC emissions from recent estimate of *Bond et al.* [2004].

The Direct Radiative Forcing (DRF) is estimated in both shortwave (SW) and longwave (LW) spectrums, at the top of atmosphere (TOA) and at the surface by calling the radiation routine with and without the presence of BC. There is no feedback of the BC on the simulated meteorology. The radiative effect of BC in the LW spectrum is negligible [*Reddy et al.*, 2005b] and is not presented in this paper. We present atmospheric absorption of shortwave radiation as the difference between the DRF at TOA and surface.

3. Results

3.1. Black Carbon Budget

The carbonaceous aerosol transport in the LMDZ GCM was thoroughly validated against measurements. The model simulated BC surface concentrations and absorption optical depth, which mostly stems from BC in industrial regions, were compared [*Reddy and Boucher*, 2004; *Reddy et al.*, 2005a]. The model performed generally well but has a tendency to underestimate BC concentrations and absorption. The BC emission inventory used in the present study is different from the one used in *Reddy and Boucher* [2004]. A comparison of modeled BC surface concentrations with IMPROVE measurements over North America (Fig. 1) conforms the underestimation. It has to be kept in mind when

0094-8276/06/$5.00

assessing the role of North American emissions which are likely to be underestimated.

The budget for the BC emitted from different world regions is given in Table 1. The global annual mean residence time of 5.3 days is shorter than our previous estimate of 7.2 days [*Reddy and Boucher*, 2004]. As mentioned above, the present study does not include open biomass burning, which are located in dry regions, result in longer residence times. The atmospheric residence time of BC emitted from different regions varies by a factor of 2. The longer residence time is for the regions with lower rainfall or dry regions (west Asia and Africa), and the shorter residence time is for regions with large precipitation or wet regions (Europe, North America, and oceanic regions).

The East and South Asian regions account for more than 50% of the global anthropogenic BC emissions. In their respective regions China and India account for most of the emissions. These emissions are from the transport sector and from biofuels which suffer from an inefficient combustion [*Reddy and Venkataraman*, 2002a, 2002b; *Streets et al.*, 2002]. Domestic coal combustion in East Asia also accounts for a considerable fraction of BC emissions in this region. The contribution of different regions to the global burden follows the corresponding contributions to emissions. The largest contribution to the burden is from East Asia (37%) followed by South Asia (16%), Africa (14%), Europe (12%), North America (10%), South America (16%), West Asia (4%), Australia (<1%) and Oceanic regions (< 1%). Relatively longer atmospheric residence time for African emissions result in contribution of about 15% to global BC burden, compared to contribution of 10% to emissions.

On the global scale biofuels account for about 34% of total BC emissions. Biofuels are the predominant source of BC over Africa (72%), South Asia (68%). They also contribute moderately to BC emissions over South America (25%) and East Asia (29%). Over East Asia the majority of the emissions are from inefficient coal combustion in the domestic sector. The respective contributions of emissions from fossil fuels and biofuels from different regions translate into corresponding contributions to the global atmospheric burden and radiative forcing.

3.2. Inter-Regional Transport

The BC atmospheric residence time of order of 5 to 7 days results in transport of emissions from one region to other regions of the world. Over all of the continental regions (except over WCA & AUP) emissions from the same region account for majority of the atmospheric BC burden (Table 3). Over North America, East and South Asian emissions contribute to 18% and 6% of total BC burden from eastward transport, respectively. On the other hand North American emissions account for only 5% of BC over Europe. Over South and East Asia, their local emissions account for more than 80% of BC burden with complements from other regions. The estimated BC burden over Australia is smaller by a factor 3 to 4 compared to other regions. Interestingly BC over Australia is mostly transported from other parts of the world with a contribution of 32%, 14%, and 9% from East Asia, Africa, and South America, respectively. Over the oceanic regions East and South Asia are dominant contributors. In the future the relative strengths of emissions and transport between different regions are expected to change.

3.3. Atmospheric Absorption of BC

Following the atmospheric loadings the largest DRF at TOA by BC is predicted over East and South Asian regions with annual mean forcings larger than +2 Wm^{-2} locally (Fig. 3). One of the striking features is that emissions from East Asia spread all most entire Northern Hemisphere (NH) with significant forcing over the west coast of USA. The radiative forcing from ship emissions is smaller than +0.005 Wm^{-2} over any part of the world. The BC emissions projected to grow over the Asian region [*Streets et al.*, 2004] in the coming decades resulting in an even larger radiative forcing.

The total global annual mean DRF at TOA from fossil fuels and biofuels is +0.2 W m^{-2}. This estimate is more than a factor of two smaller than our previous estimate (+0.54 Wm^{-2}) [*Reddy et al.*, 2005b]. The differences between the two estimates arises from difference in BC emissions. The present annual emissions (4.8 Tg yr^{-1}) are more than a factor of two smaller than that of *Reddy et al.* [2005b]. The global annual DRF at surface is –0.3 Wm^{-2} resulting in an atmospheric forcing of +0.5 Wm^{-2}. The global annual mean DRF at surface and TOA closely follows the emissions from the respective regions (Fig. 4). Once again the largest atmospheric forcing is from emissions from East Asia (+0.17 Wm^{-2}) and South Asia (+0.08 W m^{-2}).

To assess the regional contributions to the climate impacts of BC through change in the albedo of ice and snow, we also estimate the contribution of different regions to deposition of BC north to 60°N and south to 60°S. Previous studies suggest that radiative forcing at TOA from change in snow/ice albedo is +0.15 W m^{-2} or about one fourth of the DRF at TOA. The total deposition of BC over these regions is 0.20 Tg yr^{-1} (0.18 and 0.02 Tg yr^{-1} from wet and deposition, respectively), or about 4% of global BC deposition. As expected, 98% of this deposition occurs over the Northern Hemisphere (NH). The largest contribution to deposition over these regions is from Europe (63%), followed by East Asia (17%) and North America (11%). All other regions together account for the remaining 9% of total deposition. The proximity of North America, Europe, and East Asia to the snow/ice covered areas result in large contributions. The cumulative annual deposition of BC north to 60°N ranges between 5 and 10 mg m^{-2}. The deposition could reduce the snow/ice albedo by about 10-15%. This decreased surface albedo may accelerate the melting of the snow [*Hansen and Nazarenko*, 2004].

4. Conclusion

We have estimated the regional contributions to the global BC burdens and direct radiative forcing. The largest contribution to global annual mean BC burden is from East Asia (36.8%), followed by South Asia (15.6%), Africa (13.6%), Europe (11.8%), North America (10.0%), South America (6.5%), West Asia (4.5%), Australia (0.7%), and oceanic regions (0.6%). The regional contributions to atmospheric burden largely follows emissions from the respective regions. The atmospheric residence time for BC emissions from different regions varies between 4.6 to 7.3 days. The BC emissions from South and East Asia reach North America and account for about 20% of the total burden. Europe is the largest contributor to the BC deposition over the high latitudinal regions but the contribution of North America may be underestimated. It would be of interest to understand the climate response of BC deposition over the high latitudinal regions through changes in the ice albedo.

Acknowledgments. This work was supported by the Environment and Climate Programme of the European Community (PHOENICS contract EVK2-CT-2001-00098). Computing time was provided by IDRIS under project 041167.

References

Bond, T. C., et al., A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res., 109*, D14203, doi:10.1029/2003JD003697, 2004.

Hansen, J., and L. Nazarenko, Soot climate forcing via snow and ice albedos, *Proc. Natl. Acad. Sci. USA, 101*, 423–428,2004.

Hauglustaine, et al., Interactive chemistry in the Laboratoire de Météorologie Dynamique general circulation model: description and background tropospheric chemistry evaluation, *J. Geophys. Res., 109*, D04314, doi:10.1029/2003JD003957, 2004.

Jacobson, M. Z., Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols, *J. Geophys. Res., 106*, 1551–1568, 2001.

United Nations, *Clearing the Air: 25 years of the Convention on long-range transboundary air pollution*, J. Sliggers and W. Kakebeeke (Edi.) , 180 pages, Geneva, 2004.

Ramaswamy, V., et al., Radiative Forcing of Climate Change, in *Climate Change 2001, The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC*, edited by J. T. Houghton *et al.*, pp. 349–416, Cambridge University Press, 2001.

Reddy, M. S., and O. Boucher, A study of the global cycle of carbonaceous aerosols in the LMDZT general circulation model, *J. Geophys. Res.*, D14202, doi:10.1029/2003JD004048, 2004.

Reddy, M. S., and C. Venkataraman, Inventory of aerosol and sulphur dioxide emissions from India: II Fossil Fuels, *Atmos. Environ., 36*, 699–712, 2002a.

Reddy, M. S., and C. Venkataraman, Inventory of aerosol and sulphur dioxide emissions from India: II Biomass combustion, *Atmos. Environ., 36*, 699–712, 2002b.

Reddy, M. S., et al., Estimates of global multicomponent aerosol optical depth and direct radiative perturbation in the Laboratoire de Météorologie Dynamique general circulation model, *J. Geophys. Res., 110*, D10S16, doi:10.1029/2004JD004757, 2005a.

Reddy, M. S., et al., Aerosol optical depths and direct radiative perturbations by species and source type, *Geophys. Res. Lett., 32*, doi:10.1029/2004GL021743, 2005b.

Streets, D. G., et al., On the future of carbonaceous aerosol emissions, *J. Geophys. Res., 109*, D24212, doi:10.1029/2004JD004902, 2004.

O. Boucher, Hadley Centre, Met Office, FitzRoy Road, Exeter EX1 3PB, United Kingdom (olivier.boucher@metoffice.gov.uk); M.S. Reddy, Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, 08542 NJ, USA (shekar.reddy@noaa.gov).

Table 1. Global Annual Budget of BC for Different Geographical Regions

Region	Emissions ($Tg\ yr^{-1}$)	Contribution of biofuels	Global Dry Dep. ($Tg\ yr^{-1}$)	Global Wet Dep. ($Tg\ yr^{-1}$)	Burden ×100 (Tg)	Residence [a] Time (days)	Contribution to surface deposition north to 60°N and south to 60°S
SAM	0.314 (6%)[b]	5%[c] (25%)[d]	0.049	0.265	0.452 (6.5%[e])	5.28	1%
NAM	0.522 (11%)	6% (20%)	0.092	0.430	0.697 (10.0%)	4.80	11%
AFR	0.483 (10%)	21% (72%)	0.088	0.395	0.947 (13.6%)	7.16	1%
EUR	0.602 (12%)	5% (13%)	0.128	0.474	0.823 (11.8%)	5.01	63%
WCA	0.157 (3%)	1% (11%)	0.040	0.117	0.312 (4.5%)	7.29	2%
SAS	0.602 (13%)	25% (68%)	0.120	0.483	1.086 (15.6%)	6.59	2%
EAS	2.038 (43%)	36% (29%)	0.333	1.708	2.565 (36.8%)	4.60	17%
AUS	0.036 (1%)	<1% (14%)	0.006	0.030	4.062 (0.7%)	4.62	1%
OCE	0.036 (1%)	– (–)	0.007	0.029	0.042 (0.6%)	4.24	2%
Global	4.791	34%[f]	0.860	3.931	6.970	5.32	–

[a]Residence time is estimated as the ratio of burden to the sources (or sinks) of BC. [b]% contribution of each region to global emissions; [c]% contribution of each region to global BC emissions from biofuels; [d]% contribution of biofuels to energy-related BC emissions in the respective regions; [e]% contribution to global burden; [f]% contribution of biofuels to global energy-related BC emissions;

Table 2. Contribution (%) of Each Region to the BC Load over the World Regions

Source Region	Receptor Region								
	SAM	NAM	AFR	EUR	WCA	SAS	EAS	AUP	OCE
SAM	88.3	1.0	1.8	0.2	0.5	0.2	0.2	9.4	7.9
NAM	1.5	70.1	3.1	4.7	3.9	0.7	1.1	0.6	11.2
AFR	5.0	1.6	63.6	2.8	7.6	2.0	0.9	14.3	12.6
EUR	0.3	2.1	12.4	76.2	27.5	1.8	5.6	0.2	6.4
WCA	0.1	0.6	6.5	7.0	38.2	4.5	1.4	0.2	2.1
SAS	0.6	6.2	6.9	3.0	12.5	84.7	9.1	2.2	15.4
EAS	3.6	17.6	5.3	5.5	9.5	5.9	81.4	32.5	42.5
AUP	0.2	0.0	0.0	0.0	0.0	0.0	0.0	39.3	1.0
OCE	0.5	0.6	0.4	0.5	0.3	0.1	0.2	1.4	1.0

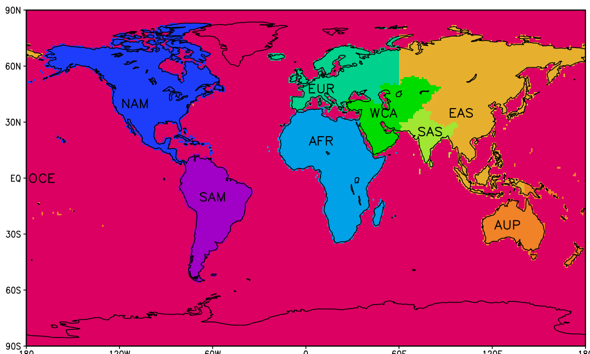

Figure 1. Different regions used in the study. SAM: South America; NAM: North America; AFR: Africa; EUR: Europe; WCA: West and Central Asia; SAS: South Asia; EAS: East Asia; AUP: Australia and Pacific Islands; and OCE: Oceanic Regions;

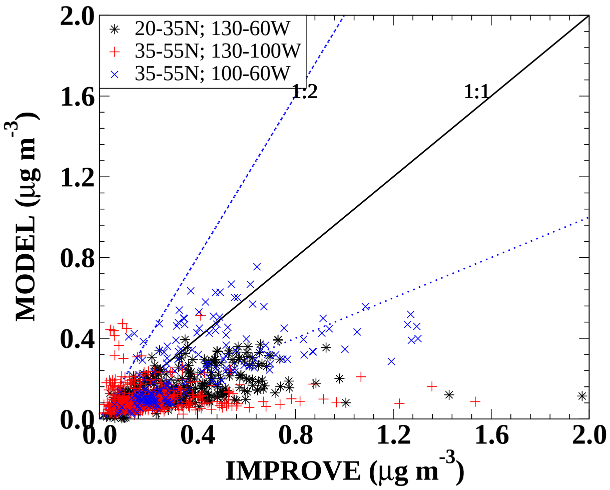

Figure 2. Comparison of model predicted monthly mean BC concentrations with IMPROVE measurements over the USA. The solid line is the 1:1 line while the dotted lines are the 1:2 and 2:1 lines. The model concentrations are sampled according to IMPROVE sampling strategy for the year 2000. For the purpose of this comparison we include all BC emission sources (fossil fuels, biofeuls, and open biomass burning) in the model estimates.

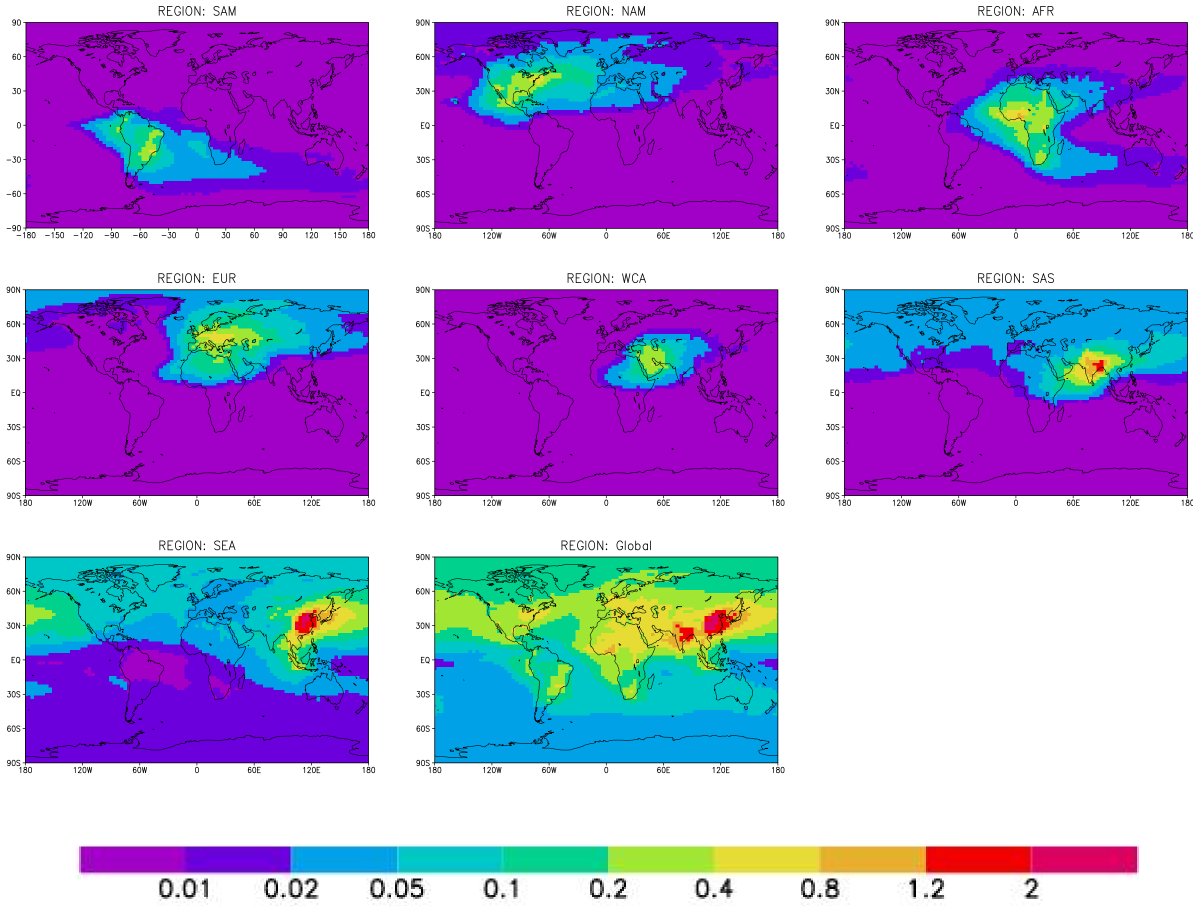

Figure 3. Global distribution of all-sky SW DRF (W m^{-2}) at TOA due to BC emissions from different geographical regions. DRF from Australia and oceanic regions are not shown because small.

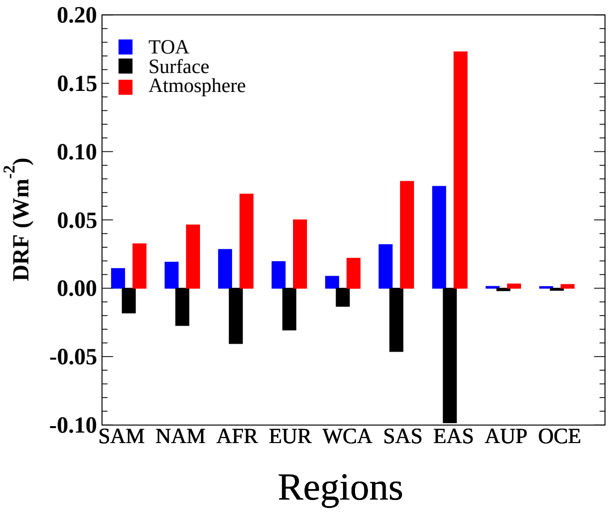

Figure 4. Global annual mean all-sky SW DRF at TOA (left bar), at surface (middle bar), and in the atmosphere (right bar) by BC emissions from different regions.